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INVESTIGATIONS OF TURBULENCE, MICROBUBBLES, ACOUSTIC STREAMING,--ETC(U)
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 82-0672	2. GOVT ACCESSION NO. AD-A118922	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INVESTIGATIONS OF TURBULENCE, MICROBUBBLES, ACOUSTIC STREAMING, NONLINEAR WAVE PHENOMENA AND HEAT TRANSFER IN LIQUID HELIUM		5. TYPE OF REPORT & PERIOD COVERED Final 1 Oct 76 - 31 Mar 82
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles W. Smith		8. CONTRACT OR GRANT NUMBER(s) AFOSR 76-3113
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Maine Department of Physics & Astronomy Orono, Maine 04469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2301/A5
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NP Building 410 Bolling AFB DC 20332		12. REPORT DATE Mar 1982
		13. NUMBER OF PAGES 12
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report represents a summary of project takk 2301/A5, Grant No. AFOSR 76-3113 covering a 66 month period beginning 1 Oct 76 and ending 31 Mar 82. Other types of reporting of the accomplishments of this project have taken three forms: 1) We have submitted five annual Scientific Reports to the Air Force Office of Scientific Research describing significant accomplishments and containing factual discussions of research discoveries. 2) We have published a total of nine papers in refereed scientific or technical journals covering major accomplishments and important observations resulting from this project.

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3) We have presented sixteen reports at meetings (two at international conferences) of professional societies for public and professional information and discussion.

We feel that this project has been very productive and has lead to a clearer understanding of nonlinear wave phenomena in liquid helium, generation of turbulence in liquids and acoustic enhancement of heat transfer at a liquid-solid interface. We present this final summary in a format similar to that of the Annual Scientific Report and discuss each topic in chronological order.

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FINAL SCIENTIFIC REPORT

"INVESTIGATIONS OF TURBULENCE, MICROBUBBLES, ACOUSTIC STREAMING, NONLINEAR WAVE PHENOMENA AND HEAT TRANSFER IN LIQUID HELIUM"

This final report represents a summary of project task 2301/A5, grant number AFOSR 76-3113 covering a 66 month period beginning 1 October 1976 and ending 31 March 1982. Other types of reporting of the accomplishments of this project have taken three forms: 1) We have submitted five Annual Scientific Reports to the Air Force Office of Scientific Research describing significant accomplishments and containing factual discussions of research discoveries. 2) We have published a total of nine papers in refereed scientific or technical journals covering major accomplishments and important observations resulting from this project. 3) We have presented sixteen reports at meetings (two at international conferences) of professional societies for public and professional information and discussion.

~~We~~ feel that this project has been very productive and has lead to a clearer understanding of nonlinear wave phenomena in liquid helium, generation of turbulence in liquids and acoustic enhancement of heat transfer at a liquid-solid interface. We present this final summary in a format similar to that of the Annual Scientific Report and discuss each topic in chronological order.

A. SUBHARMONIC, HARMONIC AND ULTRAHARMONIC RESPONSE OF LIQUID HELIUM TO ULTRASOUND IN THE LOW MEGAHERTZ RANGE

The nonlinear response of liquids to finite amplitude sound includes the generation of harmonics of the fundamental frequency as well as subharmonics and ultraharmonics. We have measured the acoustic response of liquid helium in the temperature range $1.3K < T < 4.2K$ for frequencies 0.3, 1.0, 2.8, and 10.0 MHz. At high displacement amplitudes, we observe subharmonic frequencies (f_0/n, where $n = 2, 3, 4, \ldots$ of the applied frequency f_0, harmonics of the applied frequency and harmonics of each subharmonic, ultraharmonics (mf_0/n where $m = 2, 3, 4, \ldots$ and $n = 2, 3, 4\ldots$), above specific threshold displacements. We observe signals out to $n = 10$ and $m = 13$, before background noise masks the response. The $f_0/2$ signal is greater than each of its ultraharmonics at all displacement amplitudes measured. This is observed to be the case for each subharmonic. We add that our measurements were taken for decreasing amplitudes. This method provided the most consistent results because of details involved in the temperature control technique. Threshold measurements for increasing amplitudes did not show any measureable deviation from the data for decreasing amplitudes but took considerably longer to stabilize between readings. We have examined various models for subharmonic generation. The bubble model predicts subharmonic response thresholds which are from one to two orders of magnitude larger than we observe. This is clear evidence that bubble oscillation is not the primary mechanism determining the subharmonic response threshold and growth at low-velocity amplitudes. It is interesting to note however that the viscous damping contribution to the predicted thresholds is similar, both in magnitude and temperature dependence, to the data.

The parametric amplification model estimates order-of-magnitude correct subharmonic response thresholds for f_0 = 1 MHz. However, it predicts a linear dependence upon frequency because α_1 is proportional to ω^2. Below T_λ we observe strictly equal thresholds for $\omega/2\pi$ = 1, 3, and 10 MHz. In addition to this incorrect frequency dependence, this model suggests that the subharmonic response threshold should show a lambda-like anomaly near T_λ in proportion to the large first sound attenuation observed at that temperature. We observe a decrease in the $f_0/2$ threshold for T = 2.11 K with respect to that at T = 2.00 K and T = 2.20 K. We clearly observe an increased capability of the system to generate large subharmonic signals in a region where the compressibility is strongly pressure dependent that is, within ± 50 millikelvin of the lambda point. Induced nonlinearities of order 10% are possible within one cycle of a large amplitude pressure wave (P_A = 20 mbar). We believe these results are strong indicators that the bulk thermodynamic properties of liquid are responsible for subharmonic generation. Parametric amplification in the nonlinear responses of the system could sustain the subharmonic signals observed but we feel that it is the general thermodynamic properties that favor the generation of the subharmonic response, especially in the light of the incorrect frequency dependence predicted by the parametric amplification model.

In summary, we find that the magnitude and temperature dependence for the $f_0/2$ response threshold argue against the bubble model for subharmonic generation. The observed frequency independence of the $f_0/2$ threshold argues against parametric amplification as the primary mechanism. We conclude that it is the general nature of the pressure dependence of the compressibility of liquid helium as well as other nonlinear aspects of the bulk thermodynamic properties that are responsible for the nature of the subharmonic responses and not details of specific mechanisms like microbubble oscillations or parametric amplification as might be the case in more conventional liquids.

B. GENERATION OF TURBULENCE BY ULTRASOUND IN He II.

We immersed in liquid helium a one curie tritium source, a grid and a collector-guard ring combination. Voltages applied to the source and collector select the appropriate charge species (electron bubble or positive ion) from near the source and inject a current into the region between grid and collector. A PZT4 thickness mode transducer resonant at $\omega/2\pi = 1$, 3 or 10 MHz was mounted in the grid-collector region. We then observed the current as the displacement amplitude of vibration of the transducer was increased. We observed: (1) Positive currents are independent of sound amplitude for $1.3K \leq T \leq 2.0K$. (2) Negative currents are strongly attenuated above a threshold displacement amplitude, A_c, for $T \leq 1.80K$. (3) The rapid increase in this attenuation between T = 1.80K and T = 1.60K is evidence that the electron bubbles are trapped by quantized vortex lines, as it is known that electron bubble lifetimes on vortex lines increase from less than 1 second at T = 1.80K to approximately 1000 second at T = 1.60K. We conclude from these experiments that ultrasound can generate bulk turbulence and that this turbulence may be probed by the negative io in liquid helium for $T \leq 1.80K$. Research on this effect showed that the onset of turbulence required a critical fluid velocity $v_c = \omega A_c$ which was independent for ω for $\omega/2\pi = 1$, 3 and 10 MHz, and was found to be $v_c = 0.15 \pm 0.05$ cm/s.

We have extended these measurements to the non-equilibrium dynamics of the vortex tangle. Analysis of current changes when the ultrasound is turned on and when it is turned off demonstrated clearly that the Vinen equation for the dynamics of homogeneous superfluid turbulence is valid. This was the first experimental confirmation of this equation outside the usual thermal counterflow geometry for which it was derived and repeatedly tested. Through a least squares fitting routine of the equilibrium currents versus sound amplitude and a modeling of the sound on-off current responses we have established values for the coefficients for the growth and decay terms contained in the Vinen equation. In addition, we have made the first experimental determination of the capture width for electron bubbles on vortex line in a turbulent He II tangle away from boundaries. We consider this work a significant contribution to the physics of turbulence in liquid helium.

One of the advantages of our technique is the added parameter frequency. We have accumulated a body of data on the dynamics of vortex tangle growth and decay over a range of frequencies. We wish to emphasize a significant discovery. The threshold for the generation of the $f_o/2$ subharmonic is the same as the threshold for the generation of quantum turbulence and this threshold corresponds to a critical velocity, $v_c \approx 0.3 \pm .05$ cm/s. This has been verified for $\omega/2\pi = 0.3, 1.0, 2.8$ and 9.6 MHz. The subharmonic response is clearly associated with the turbulent state and the threshold is given by $\omega A = 0.3$ cm/s where A is the displacement amplitude.

C. ACOUSTO-OPTICAL TECHNIQUES TO MEASURE LIQUID NONLINEAR PROPERTIES

In much research and many applications of finite amplitude ultrasound it is important to detect and characterize the acoustic response of the sonicated liquid. In particular, it is useful to detect the presence of the subharmonic and the threshold for collapse or transient cavitation. A variety of techniques have been developed for this purpose.

In our work, observations were made of the diffraction patterns produced by the acousto-optic effect in superfluid helium and in methanol for both cylindrical and plane wave sound fields. Thresholds for the subharmonic of order 1/2 and transient cavitation were determined by observation of abrupt changes in the diffraction patterns. The onset of the subharmonic produced additional diffracted signals in a stable diffraction pattern while onset of cavitation completely disrupted the diffraction pattern.

We have found that the acousto-optic method has many advantages: it requires a simple experimental arrangement; it does not disturb either the sound field or flow fields in the liquids; it presents information only from the region of the sound field of interest; the data acquisition is very rapid, and the laser beam can be scanned throughout the volume of interest. The results are generally applicable and we have observed similar changes in the diffraction patterns for more usual liquids including water and methanol when sonicated in the megahertz frequency range. This technique has several distinct advantages with respect to other detection methods and may be useful in a variety of applications.

In addition, we have begun to use an acousto-optic technique to measure the nonlinear parameters of cryogenic liquids. In these studies a laser beam is diffracted by the sound field. For low sound amplitudes the diffraction pattern formed is symmetric with respect to zero order diffraction. For higher amplitudes this pattern becomes asymmetric as the propagating waveform becomes distorted because of the nonlinear parameters of the propagation medium. We have carried out the first continuous quantative measurements of the intensity asymmetries of the diffraction patterns to fifth order of a clean laser beam as it traverses a region of ultrasonic waves. Our results for methonal and liquid nitrogen are in good agreement with the B/A nonlinearity ratios for these liquids as measured by other techniques. Preliminary results look very interesting for liquid helium below the superfluid transition. This work will eventually result in a publication and a thesis if support for continuation can be found. It appears that it is necessary to include third order effects (C/A ratios) in the case of liquid helium, even relatively far away from the superfluid transition.

D. ACOUSTIC STREAMING IN LIQUID HELIUM

The propagation of sound in an absorptive medium gives rise to mass flow. This phenomenon is known as acoustic streaming. It is a second order nonlinear effect.

The experimental cell consists of a tritium source and grid arranged to inject a well defined beam of negative ions (electron microbubbles) onto a pair of guarded collectors 2.0 centimeters away, spaced 0.03 centimeters apart. A plane wave first sound beam, generated with a PZT4 thickness mode transducer resonant at 9.87 megahertz, was directed orthogonal to the ion beam and filled the drift space region. In the presence of acoustic streaming the negative ion beam was observed to translate from the first collector to the second collector in the direction of sound propagation. Knowing the geometry and the negative ion mobility, streaming velocities as small as 0.01 centimeters/second could easily be measured.

We observed the acoustic streaming velocity as a function of sound displacement velocity frequency and temperature. The streaming velocity is proportional to the square of the displacement velocity up to 0.053 $(cm/s)^2$. This corresponds to the intensity threshold for the ultrasonic generation of vortex line. For increased sound intensity, after a transition region, the streaming velocity is again proportional to the square of the displacement velocity. The slope of this second straight line region is less than the first since mutual friction can now couple the normal fluid component to the superfluid component and both are expected to stream.

The temperature dependence of the streaming velocity for a given sound intensity is determined by the temperature dependence of the first sound absorption coefficient via the coefficient of second viscosity in detailed agreement with the theory by Khalatnikov and Boguslavskii, et.al. . By repeating the above types of measurements at 1 MHz and 3 MHz (in addition to the 10 MHz results discussed) we have also verified the frequency squared dependence of the streaming velocity which comes into the problem via the first sound absorption coefficient, α.

E. SUBHARMONIC GENERATION/BIFURCATION IN LIQUID HELIUM

Measurements of the finite-amplitude first-sound response of liquid helium-4 show a complicated acoustic subharmonic spectrum. Above the superfluid transition, $T_\lambda = 2.17$ K, liquid helium behaves macroscopically as a classical liquid. One observes a very rich nonlinear response, dominated by vapor bubble dynamics of the type recently carefully documented for the case of water. This includes a subharmonic route to chaos (acoustic cavitation), but does not show bifurcation of the Feigenbaum type. However, below the superfluid transition where the existence of conventional vapor bubbles is excluded by quantum-fluid properties, one observes not only a sharper subharmonic spectral response but a well defined bifurcation sequence which quantitatively exhibits the Feigenbaum convergence ratio, $\delta = 4.669 \ldots$

The first subharmonic, $f_0/2$, appears for a drive voltage on the ultrasonic transducer which corresponds to a sound displacement velocity of 0.15 cm/s. As the sound intensity is increased, other subharmonics as well as ultraharmonics appear. The convergence ratio, δ was calculated by using linear regression analysis to estimate the onset threshold of each subharmonic of the first three components of the first subharmonic-bifurcation sequence f_0/n where n = 2, 4, and 8. Four independent sets of data at 1.60 K yield $\delta = 4.83 \pm 0.6$ in quantitative agreement with the predicted value. Determinations at two other temperatures and at $f_0 = 9.8751$ MHz fall within the above range. Attempts to measure the rescaling factor μ for fully developed adjacent members of the bifurcation sequence have met with less success. Analysis limitations arising from the combined effects of the $f_0/4$ peak to phase lock to nearby subharmonics permit us only to place a range of 6-10 dB on the scaling parameter. However, this result is not in conflict with the predicted value of 8.2 dB.

Above the superfluid transition one still observes subharmonics. The threshold for the generation of $f_0/2$ is larger. Bifurcation of the Feigenbaum type is not present: $f_0/4$ is difficult to generate and all peaks appear broader and set upon a noisy background.

Using a gated tritium source, an appropriate drift space, and a guarded collector, one can produce a current of negative ions (electron microbubbles) with which to probe the sound field. If quantum vortex e is present, ions can be trapped on the line and the current to the collec will decrease. We observe that as the sound-pressure amplitude is incr d from zero, no ion trapping occurs until the threshold for the product the first subharmonic-bifurcation sequence is exceeded. This effects is large and has the unmistakable lifetime edge and polarity dependence for ion trapping on vortex line. In this manner, for the case of acoustic subharmonic bifurcation in superfluid helium, we identify the physical aspect associated with the universal convergence as the threshold for the production of quantum turbulence (vortex-line generation), not the threshold for the production of classical turbulence by sound (acoustic cavitation), which lies 2 orders of magnitude higher in sound-pressure amplitude.

It should be emphasized that to date only three other types of experiments quantatively show the Feigenbaum period doubling bifurcation universalities. These are Rayleigh-Benard experiments, couette flow experiments and nonlinear discrete electronic circuits. The discovery of universality in He-II first sound subharmonic generation represents the first example of this fundamental property in a quantum system.

F. HEAT TRANSFER AT A SOLID-LIQUID INTERFACE (COPPER AND LIQUID HELIUM)

In a conventional Kapitza resistance experiment involving heat transfer across a copper surface into liquid helium an acoustic streaming velocity field (at 10 MHz) was directed transverse to the surface normal. Ultrasound had no observable effect on the heat transfer to the superfluid phase (He-II) but in the normal fluid phase (He-I) the thermal conductance increased linearly with acoustic velocity amplitude, reaching a value 2.5 times the zero sound conductance for a sound velocity amplitude of 0.8 centimeters/second. We feel these factors are important in the design of cryogenic heat exchanges, heat sinks and superconducting machinery.

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